Photons as Ultra High Energy Cosmic Rays ?

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We study spectra of the Ultra High Energy Cosmic Rays assuming primaries are protons and photons, and that their sources are extragalactic. We assume power low for the injection spectra and take into account the influence of cosmic microwave, infrared, optical and radio backgrounds as well as extragalactic magnetic fields on propagation of primaries. Our additional free parameters are the maximum energy of injected particles and the distance to the nearest source. We find a parameter range where the Greisen-Zatsepin-Kuzmin cut-off is avoided.

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Introduction. Measurements of the spectra of the Ultra High Energy Cosmic Rays (UHECR) [1] show that the Greisen-Zatsepin-Kuzmin (GZK) cutoff [2] is absent. The resolution of the arising puzzle seems to be impossible without invoking new physics or extreme astrophysics, for reviews see Refs. [3,4]. Clearly, the GZK cutoff is avoided if the distribution of sources is peaked in our local cosmological neighborhood, or if the primary particles are immune to the Cosmic Microwave Background Radiation (CMBR). First possibility can be realized e.g. in the model of decaying superheavy dark matter clustered in the galaxy halo [5]. Second possibility requires either new hypothetical particle [6], or violation of the Lorentz invariance [7], or extreme neutrino luminosity if Z-burst model is employed [8].

In this Letter we address the question: is it really impossible to avoid the GZK-cutoff within frameworks of the standard physics if the distribution of (astrophysical) sources is homogeneous ? At a first glance, the answer is negative. However, one should be more careful and recall that in the models of decaying topological defects the sources are homogeneously distributed throughout the Universe while the products of the decay are all standard particles. Nevertheless, the model proves to be working [9]. Prime reasons for success are specific injection spectra and a large fraction of UHE photons. Can the same work for astrophysical sources ? One can argue against this conjecture that topological defects are invisible, except of their UHECR flux, and therefore it is possible that the distance to the closest fraction of the decaying defect network is not large. This fraction may make a dominant contribution even if the network itself is homogeneous. In contrast to this, there are no suitable astrophysical sources within the GZK sphere. This argument is valid, but not without a caveat. Astrophysical sources may be "invisible" as well. Among suggested candidates are gamma-ray bursts [10] and "dead" quasars [11]. Both form a homogeneous population and were assumed to work without invoking new physics. Prime motivation was invisibility of these sources which resolves the puzzle that rays do not point back to any visible candidate sources within the GZK sphere. However, because of the homogeneous distribution of respective sources these models should exhibit the GZK cut-off in general. The analysis of whether it is possible to avoid the cut-off and under which conditions was not carried out. The same danger exists in Z-burst models as well. Indeed, Z-bursts occur homogeneously throughout the Universe (unless background neutrino are extremely clumped) which provides a homogeneous source of protons and photons and therefore the model is subject to the GZK cut-off in principle.

Recently, highly significant correlations of arrival directions of the UHECR with BL Lacertae were found [12]. Distances to more than a half of BL Lacs are not known. Closest BL Lacertae with known redshifts are at $z \sim 0.03$ and therefore outside of the GZK sphere. Do such correlations require new physics ? To be sure one should first firmly exclude standard model particles without making strong assumptions on the injection spectra.

Methods. We use numerical code which was developed in [13]. We calculate propagation of protons and photons using standard dominant processes (for details see [3]). For protons we took into account single and multiple pion production, and $e^{\pm}$ pair creation. For photons we considered $e^{\pm}$ pair production, inverse Compton scattering and double pair production processes. For electrons and positrons we took into account Compton scattering, triple pair production and synchrotron energy loss on EGMF. Propagation of protons and photons is calculated self-consistently. Namely, secondary (and higher generation) particles arising in all reactions are propagated alongside with the primaries. UHE protons and photons lose their energy in interactions with the electro-magnetic background, which consist of CMBR, radio, infra-red and optical components, as well as Extra Galactic Magnetic Fields (EGMF). Protons are sensitive essentially to CMBR only, while for photons all

components of the electro-magnetic background are important. We take a minimal model for the radio background [14]. For calculating the infra-red/optical background we used the same approach as in [15]. For the extragalactic magnetic field only the upper bound is established observationally, $B < 10^{-9}\mathrm{G}(l_c/\mathrm{Mpc})^{1/2}$ [16]. It is believed that galactic magnetic fields can be generated from the extragalactic "seed" if the later has magnitude in the range $B = 10^{-12} - 10^{-9}G$, but in some regions it can be much smaller (voids) or larger (sheets). In our simulations we vary magnetic field strength in the range $B = 10^{-12} - 10^{-9}G$, assuming an unstructured field along the propagation path.

Results. Astrophysical sources imply acceleration mechanism of the UHECR production, therefore protons always exist as primaries. We study their propagation first. We assume power law injection spectra, $J \propto E^{-\alpha}$. To start with, we study the dependence of the observed spectra on the value of α assuming homogeneous distribution of sources, no evolution in comoving volume, and we place no restrictions on the distance to the nearest source. Resulting spectra are shown in Fig 1.

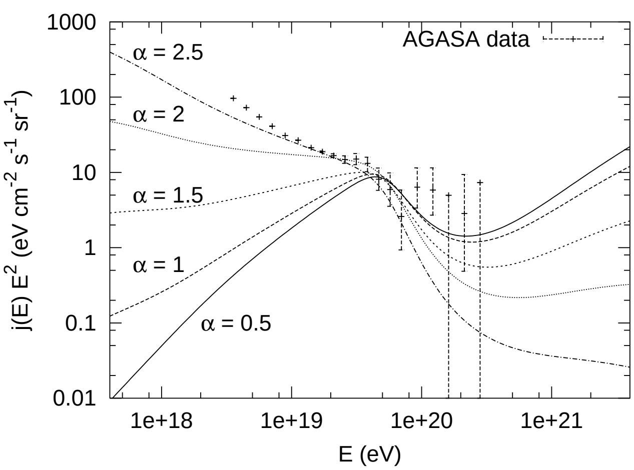

FIG. 1. Proton spectra for various values of the power law index α.

The GZK cut-off is clearly seen in all cases, but its impact is different depending on α. "Hard" injection spectra, $\alpha \lesssim 1.5$, can be nearly reconciled with the data provided some other component of cosmic rays (Galactic) exists at $E \lesssim 10^{19}$ eV. Note that injection spectra arising in the Z-burst model can be roughly approximated by $\alpha \lesssim 1$ while those arising in the decaying topological defects model can be approximated by $\alpha \sim 1.5$. Astrophysical acceleration mechanisms often result in $\alpha \gtrsim 2$ [17], however, harder spectra, $\alpha \lesssim 1.5$ are also possible, see e.g. [18].

Different models of UHECR generation can be discriminated if sources are identified and distances to them are known. Unfortunately, identity of particular sources is lost in the overall spectrum of Fig. 1 and one has to construct the observed spectra of individual sources as a function of the distance. This procedure was carried out in Ref. [19], however, the wealth of information arising with this treatment may be prohibitive for presentation in a Letter. We represent it in the following way. First we construct individual spectra as a function of z. For each given spectra we find the value of energy at which the number of particles per decade of energy becomes smaller than the freely propagated particle flux by a given factor. (3, 10, etc.) We plot energy thus obtained as a function of z. Results are presented in Fig. 2. We see that curves with an increasing dumping factor converge rapidly in the range $0.01 \lesssim z \lesssim 0.5$, therefore, if the redshift to the source is in this range, Fig. 2 allows to determine maximal proton energies expected from this source.

The horizontal line at $E = E_{\mathrm{GZK}} \equiv 4 \times 10^{19}$ eV corresponds to the formal beginning of the GZK cut-off. Attenuation length at this energy is $l_a \sim 10^3$ Mpc. This may give a false impression that protons with $E = E_{\mathrm{GZK}}$ reach us from the sources located at $l = l_a$. Contribution of these protons is negligible as can be seen from Fig. 2: for $z > 0.2$ bulk of the protons have $E < 4 \times 10^{19}$ eV.

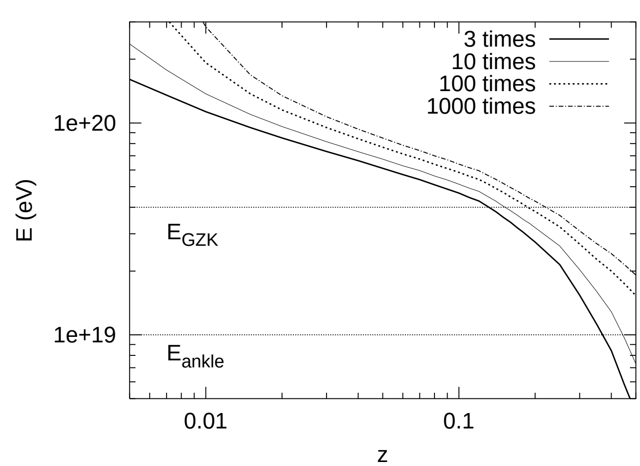

FIG. 2. Levels of a constant dumping of the proton flux as a function of distance traversed.

We conclude that the contribution of protons to the UHE spectrum from distant sources with $z > 0.5$ is negligible above AGASA ankle $E > 10^{19}$ eV, and it is negligible for sources with $z > 0.2$ in the highest energy region $E > 4 \times 10^{19}$ eV.

Let us discuss now the propagation and expected spectra of photons. Again we consider α as a free parameter. Results are very sensitive to its value. Interacting with electro-magnetic backgrounds, photons cascade to low energies which may lead to overproduction of "soft" gamma-rays. Main constraint is given by the EGRET observations in the energy range 10^8 eV - 10^{10} eV [20]. We find that injection power law spectra with indexes $\alpha \geq 2$ cannot lead to a sizable contribution to the UHECR and obey the EGRET bound simultaneously. This is valid

even for vanishing EGMF. Therefore, in what follows we consider spectra with $\alpha \lesssim 2$. With this restriction the value of EGMF becomes a crucial parameter.

We have studied the dependence of the resulting photon spectra on EGMF and on the maximum energy of injected photons for different values of α. Our first requirement was that the spectra describe highest energy cosmic ray data well. Our second requirement was that the conflict with EGRET bound does not appear. For each value of α and $E_{\max}$ this gives maximum possible value of EGMF strength, B, at which conflict does not appear. This maximum value of B does not depend significantly on the spectral shape in the range of α we have considered, $1 < \alpha < 1.75$, and is plotted in Fig. 3. Parameter space below line with a given value of α is allowed for this α and leads to resolution of the GZK puzzle with photons being primaries.

Note that the dimensionality of the parameter space is actually very large. In this letter we present only significant dependencies, while dependence e.g. on cosmological parameters (we assumed $H_0 = 70$ km/s/Mpc and $\Omega_\Lambda = 0.7$) and on the evolution of sources (we assumed no evolution having in mind possible correlations with BL Lacertae) are weak. These less essential dependensies will be discussed elswere, [21].

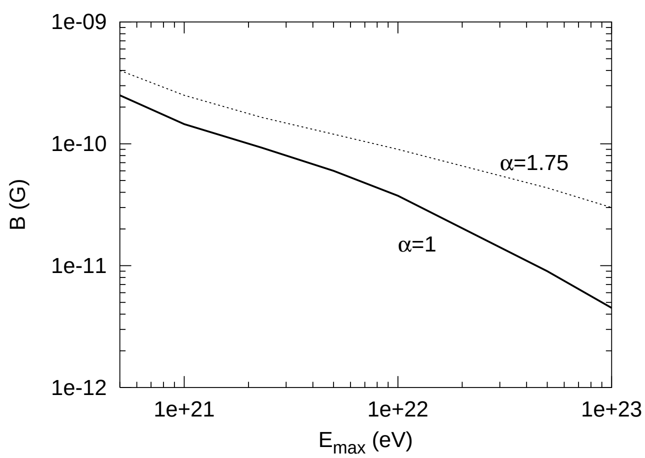

FIG. 3. Maximum allowed value of EGMF strength B as a function of maximal injection energy.

In constructing photon spectra which lead to Fig. 3, we made no restrictions on the distance to the nearest source. With such restrictions, i.e. if there are no close sources, parameter space is more narrow. In particular, if there are no sources of UHECR in the GZK volume as in the case of BL Lacertae, one could think that UHE photons cannot reach us without significant energy loss. Indeed, attenuation length of photons is less then 10 Mpc for energies $10^{19}\text{eV} < E < 3 \times 10^{20}$ eV, therefore one can think that there should be no UHE photon events with such energies. However, this is not true if the photon injection spectrum extends to large energies, $E \gg 10^{21}$ eV. For photons of this energy the attenuation length is as large as several hundred Mpc. This means that UHE photons originating with highest energies at these distances will still be cascading at energies above the GZK cut-off while approaching us. As a result they will be continuously recreating secondary photons with energies $10^{19}\text{eV} < E < 3 \times 10^{20}$ eV as well. Interestingly, we find that these secondary photons in this energy range have a power law spectrum $1/E^2$ regardless of the value of α of the initial injection spectrum.

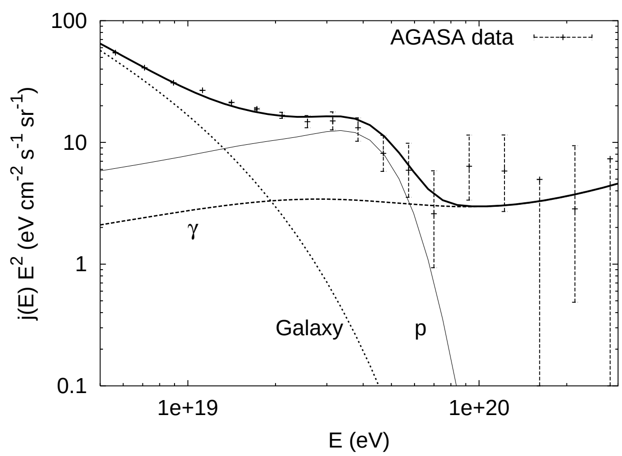

FIG. 4. Solid line shows combined contribution of proton and photon components of UHECR. AGASA data are also shown.

An example of a resulting UHECR spectrum with crussial assumtion of absence of sources withing GZK volume is presented in Fig. 4. Here we have assumed that the closest source in the distribution obeys the condition $z > 0.03$ and EGMF is small, $B = 10^{-12}G$. We also assume injection spectrum $\alpha = 1.5$ for both protons and photons. Resulting proton and photon contributions are shown separately by thin solid and short-dashed lines respectively. We describe the low end of the spectra by independent Galactic contribution which is modeled by the power law $1/E^{3.16}$ at small energies with an exponential drop at energies around the ankle, $E \sim 10^{19}$ eV. The solid line in Fig. 4 shows the sum of all components. Photons starts to dominate total UHECR spectrum with effective power law $1/E^2$ at energies $E \sim 5 - 6 \times 10^{19}$ eV. Interestingly, this is the value of energy where the clustering (small angle autocorrelations) in AGASA data set [22] becomes most significant [23].

TABLE I. Parameter choices leading to the fit as good as in Fig. 4.

$z_{\min}$	α	$E_{\max}$(eV)	N_γ/N_p
0.03	1.5	10^{23}	3
0.03	1.5	10^{22}	17
0.03	1.75	10^{23}	12
0.03	1.75	10^{22}	45
0.1	1.5	10^{23}	60

The ratio of photons to protons at injection (at given energy) which leads to the best fit; in the case of Fig. 4 is $N_\gamma/N_p = 3$. Restrictions on this parameter and on the maximal energy of injected photons are presented in Table I for different values of α. Smaller values of $E_{\max} < 10^{22}$eV do not work (unrealistically large number of photons per proton is required) because of the rapid decrease of the attenuation length for photons. Minimum distance to the closest source at $z = 0.1$ still works with the same value of EGMF. However, this nice picture is destroyed if the EGMF is larger than a few $\times 10^{-12}$ G.

Conclusions We have studied spectra of the UHECR assuming primaries are protons and photons and injection spectrum is a power law $\propto E^{-\alpha}$. With a homogeneous distribution of sources and a hard injection spectra, $\alpha < 1.5$, we find that protons can account for the observed flux at highest energies producing only a shallow dip around the GZK energy. Magnitude of the effect is not in strong disagreement with the data at the level of current statistics. Presence of (invisible) sources within GZK sphere is required, however, if protons are the only primaries. Individual sources located at $z > 0.2$ make negligible contribution into proton component at $E > 4 \times 10^{19}$ eV. Inclusion of photons makes agreement with the data better. In this case even distant sources with $z > 0.03$, such as BL Lacertae, can contribute to observed rays in the energy range $E > 10^{19}$ eV with the effective power law spectrum $1/E^2$, if injection spectrum extends up to $E_{\max} > 10^{22}$ eV and EGMF does not exceeds 10^{-12} G . Photon component becomes dominant at $E > 5 \times 10^{19} eV$. In the case when there are sources at $z \lesssim 0.1$, the suggested scenario is more economical than the Z-burst model which requires acceleration of primaries to even higher energies $E_{max} > 10^{23}$ eV. In addition, the Z-burst model requires extremely large fluxes of neutrino, while it is enough to have photon flux at the source to be larger than the proton flux by a factor of only a few.

We conclude that the GZK cut-off can be avoided with photons as primaries making perfect fit to the data. Parameter space is rather large if there are no restriction to the distance to the nearest source, see Fig. 3. We cannot rule out photons as primaries even in the case when production sites are BL Lacertae [12], which (with known redshifts) are all outside the GZK volume. To rule it out one needs a source-by-source study taking into account the concrete configuration of extragalactic magnetic fields.

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